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6. AUTHOR(S)
R. Scheps

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Naval Command, Control and Ocean Surveillance Center (NCCOSC),
Research, Development, Test and Evaluation Division (NRaD)
San Diego, CA 92152–5000

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The 1.06 μm Nd transition in co-doped Cr,Nd:$Gd_3Sc_2Ga_3O_{12}$ (Cr,Nd:GSGG) is obtained by diode pumping Cr^{3+} at 670 nm and is shown to produce efficient, low-threshold laser operation. Both cw and long-pulse diode pumping were demonstrated, with pump power levels as high as 300 mW cw and 1 W pulsed. The lowest threshold power measured was 938 μW, and the highest output power obtained was 43 mW cw and 173 mW pulsed. The best slope efficiency obtained was 42.1%, 78% of the theoretical maximum. Loss measurements indicate a value of 0.4% cm^{-1}.

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Efficient Cr,Nd:$Gd_3Sc_2Ga_3O_{12}$ laser at 1.06 μm pumped by visible GaInP/AlGaInP laser diodes

Richard Scheps
Naval Ocean Systems Center, Code 843, San Diego, California 92152

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The 1.06 μm Nd transition in co-doped Cr,Nd:$Gd_3Sc_2Ga_3O_{12}$ (Cr,Nd:GSGG) is obtained by diode pumping Cr^{3+} at 670 nm and is shown to produce efficient, low-threshold laser operation. Both cw and long-pulse diode pumping were demonstrated, with pump power levels as high as 300 mW cw and 1 W pulsed. The lowest threshold power measured was 938 μW, and the highest output power obtained was 43 mW cw and 173 mW pulsed. The best slope efficiency obtained was 42.1%, 78% of the theoretical maximum. Loss measurements indicate a value of 0.4% cm^{-1}.

Laser diode pumping of Nd:YAG lasers is well recognized for producing high-efficiency, low-threshold devices. However, accurate thermal control of the diode junction temperature is required for efficient operation of the Nd:YAG laser due to the narrow absorption bandwidth at 808 nm. Such control is cumbersome and adds complexity to the overall system. The narrow absorption linewidth also increases the difficulty of modeling both the inversion profile resulting from volumetric deposition of the polychromatic pump excitation, and the effects of anticipated spectral shifts in the pump source due to aging.[1] For diode arrays the additional aspects of the variation in the central wavelength and bandwidth from stripe to stripe must be considered. From a pragmatic point of view, the specification of a high-power narrow-band diode array increases the cost of the semiconductor pump. Because in practice the array is often the single most expensive component in the laser head, the total costs can easily become prohibitive. To address this issue, hosts for the Nd ion have been sought in which the width of the 800 nm absorption is increased. Materials such as Nd:BEL (Ref. 2) and Nd:YVO_4 (Ref. 3) are two examples of laser crystals which have been diode pumped and have a significantly broader absorption bandwidth than Nd:YAG. The present work, in which the Cr^{3+} ion is pumped at 670 nm in co-doped Cr,Nd:$Gd_3Sc_2Ga_3O_{12}$ (Cr,Nd:GSGG) represents a substantially different solution to the problem.

Cr,Nd:GSGG was originally developed to enhance[4] the coupling of flashlamp excitation to the $Nd^4F_{3/2}$ upper laser level. This is accomplished by means of the broad absorption of the Cr^{3+} ion in the visible and the rapid and efficient excitation transfer between the $^4T_2$ state of Cr^{3+} and the $^4F_{3/2}$Nd level. An additional excitation transfer process occurs through absorption of the Cr^{3+} $^4T_2 \rightarrow {}^4A_2$ fluorescence by the Nd ion. Excitation transfer is useful for diode pumping as well, as it provides an alternative channel for populating the upper laser level of Nd using the broad absorption band centered at 640 nm. With visible laser diodes of moderate power now available from commercial suppliers, the viability of this approach holds great promise. Although visible diodes are primarily of interest for pumping Cr^{3+}-doped tunable solid-state lasers,[5-7] the generation of efficient 1.06 μm Nd emission by these devices is an important demonstration of their versatility. The results of pumping Cr,Nd:GSGG using low-power, single-mode commercial laser diodes and higher power, multimode diodes are reported below.

The pump geometry, shown in Fig. 1, is a modified version of the standard polarization combination configuration used[2] to longitudinally pump Nd lasers. The present pump configuration has been described in detail elsewhere.[6] Two polarization beam combiner cubes are used in conjunction with a $\lambda/2$ plate, allowing up to three optical sources to simultaneously pump the laser rod. Initial experiments combined two 10 mW, single-mode GaInP/AlGaInP laser diodes which were positioned as shown in Fig. 1. These diodes operated at 672 and 673 nm, respectively. Higher output laser performance was achieved by pumping with a multimode[8] laser diode. Two variations of this device were used. The first had a 15 μm wide stripe and operated at a maximum power level of 100 mW cw, 265 mW long pulse ("quasi-cw"). The coherence properties of this diode were comparable to that of the commercial diodes, producing a similar pump threshold and focused spot size. The second device had a 60-μm wide stripe and generated up to 300 mW cw and 1 W long pulse. For this laser the focused spot size and threshold were degraded relative to the single-mode diodes. Both diodes were strained-layer single quantum well graded-index separate confinement heterostructure (GRINSCH) designs manufactured by McDonnell Douglas Opto-Electronics Center and are described in more detail in Ref. 8. Cooling for thermal management was utilized but not required for either of the multimode diodes. At full power the heatsink was maintained at approximately 21 °C. When used to pump the rod, one of the high-power diodes replaced a 10 mW diode laser while the other 10 mW diode was replaced with an alignment helium-neon laser. The resonator consisted of a 6.25-mm-diam, 5-mm-long Cr,Nd:GSGG rod and either a 5 or 10 cm radius of curvature (ROC) output coupler in a nearly hemispherical configuration. The exterior face of the rod was coated for high reflectivity (HR) at 1.06 μm and high transmission (HT) at 670 nm, while the interior face was antireflection (AR) coated for 1.06 μm. Two different Cr^{3+} densities were used. The rod providing the best results contained 2×10^{20} ions/cm^3 of both

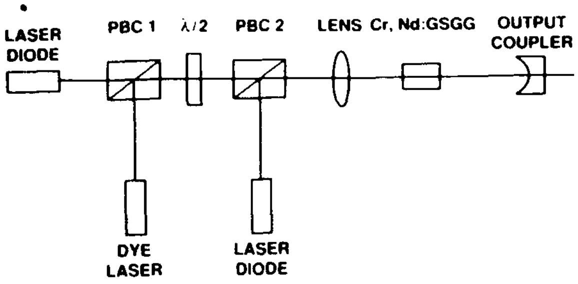

FIG. 1. Configuration of the pump and resonator optics. Two polarizing beam combiner cubes (PBC) are used to allow three optical sources to simultaneously pump the Cr,Nd:GSGG crystal. The $\lambda/2$ plate rotates the polarization of the two sources transmitted by PBC1, determining the fraction of each transmitted by PBC2.

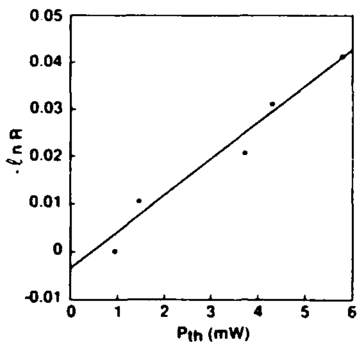

FIG. 2. Plot of linear regression fit to data showing the variation of the absorbed threshold power with output coupler reflectivity.

Cr^{3+} and Nd^{3+}. The data reported below are primarily for this rod. The second rod had the same dimensions as the first and the same Nd density ion density, but the Cr^{3+} ion density was 1×10^{20} ions/cm^3.

The absorption spectra of the uncoated rods displayed sharp Nd^{3+} lines superimposed on two broad Cr^{3+} visible absorption bands. These features were reported previously.[9] A remarkable feature of the Cr,Nd:GSGG rods used in this work is the low-measured threshold power. Using a 10 cm ROC HR output coupler, the absorbed power required to reach threshold was 938 and 985 μW for the high and low Cr^{3+}-doped rods, respectively. The threshold power was low enough so that laser emission could be obtained when using a 1 mW helium-neon laser at 632.8 nm to align the cavity. The measured threshold power compares favorably with the value of 7 mW reported[9] in an earlier study of longitudinal pumping Cr,Nd:GSGG using a Kr^+ laser at 647 nm. For Nd:YAG, threshold powers as low as 2.3 mW had been reported for a diode-pumped monolithic resonator[10] and 1 mW for a miniature "microchip" laser.[11] The comparison to Nd:YAG supports the assertion that the internal loss of Cr,Nd:GSGG is as low as high-quality Nd:YAG since the threshold power P_{th} depends directly on the resonator loss[12]

$$P_{th}=\frac{\pi(w_p^2+w_r^2)\hbar\omega(\Sigma L)}{4\sigma\tau}, \quad (1)$$

where $\hbar\omega$ is the pump photon energy, ΣL represents the sum of all intracavity (double pass) losses and includes the output coupling, w_p and w_r are the pump and resonator waists, respectively, σ is the stimulated emission cross section, and τ is the fluorescence lifetime. For Cr,Nd:GSGG[13] σ is 1.3×10^{-19} cm^2 and τ is 242 μs.

The losses in the Cr,Nd:GSGG rod were measured directly using two different techniques. The first measured the relaxation oscillation frequency, which is related[14] to the cavity losses by

$$L=(2\pi f_r)^2\frac{2\tau(n_1l_1+n_2l_2)}{P_e}, \quad (2)$$

where L represents the round-trip cavity losses including the output coupling, $P_e = (P - P_{th})/P_{th}$ is the excess pump power, P is the absorbed pump power, n_1 and n_2 are the refractive indices of Cr,Nd:GSGG (1.949) and air, respectively, l_1 and l_2 are the pathlengths through the rod and air, respectively, c is the speed of light, and f_r is the relaxation oscillation frequency. With a pump power P_e of 14.6 the oscillation frequency was measured to be 177 kHz, giving a value of 7.49×10^{-3} for the losses. Accounting for the output coupling, the round-trip internal resonator loss is 4.4×10^{-3}. Using this loss in Eq. (1) along with the measured pump waist of 5 μm and the resonator waist of 45 μm (calculated from the beam divergence), the calculated threshold power is 1.1 mW, in good agreement with the measured value. The resonator losses were also calculated from the dependence of the threshold power on output coupling.[15] The data were obtained with dye laser pumping and are shown in Fig. 2. The fit by linear regression yields a round trip loss of 3.7×10^{-3} and a slope (equal to the round-trip gain) of 7.8×10^{-3} mW^{-1}. The two values for the resonator loss are in good agreement, giving single-pass loss values of 0.44% cm^{-1} and 0.37% cm^{-1} for the relaxation oscillation and Findlay–Clay methods, respectively.

The threshold power was measured with the dye laser from 610 to 680 nm and remained constant (to within 10%) over this range. The best slope efficiency was 42.1%, obtained with a 97%R output coupler. Using the narrow stripe diode at maximum power, 22.2 mW cw and 79.4 mW pulsed were obtained. The pulse length used was 500 μs at a pulse repetition rate of 20 Hz. Diode pumping with the wider stripe multimode diode produced a slope efficiency of 22.6%, a threshold power of 57.6 mW, and maximum output powers of 42.8 mW cw and 173.0 mW long pulse. The data are shown in Fig. 3. To determine if thermal effects were degrading the output power, the cw power was monitored as a function of time and the pulsed output was monitored while varying the pump duty cycle and pulse width. For the pump-power densities used in this work no output degradation was observed. It is to be noted that the quantum defect, the ratio of pump to output photon energy, is 0.63 for the 1.06 μm transition in Cr,Nd:GSGG compared with 0.76 for the same transition in Nd:YAG pumped at 808 nm. This additional thermal loading will impact the design of a high-power diode

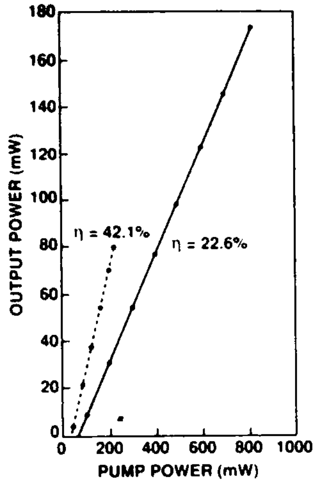

FIG. 3. Laser output power vs absorbed pump power for Cr,Nd:GSGG shown for the narrow (dashed) and broad (solid) stripe multimode diodes. Pulsed data is plotted; cw data is coincident with pulsed up to maximum cw pump-power limit. The data were obtained with a 97% R output coupler, and the slope efficiency is indicated.

pumped Cr,Nd:GSGG laser. However, some of these issues have been successfully approached in designing diode pumped 1.34 μm Nd:YAG lasers, for which the quantum defect is 0.60. Dividing the slope efficiency measured for Cr,Nd:GSGG by the quantum defect gives a photon slope efficiency of 66.8%. By further factoring out the efficiency for Cr to Nd excitation transfer, reported[9] to be 0.86, the resulting slope efficiency is as high as that reported[16] for end-pumped Nd:YAG. The maximum slope efficiency for Cr,Nd:GSGG is 54.2%, obtained from the product of the quantum defect and the excitation transfer efficiency.

In summary, Cr,Nd:GSGG pumped by visible diodes has been shown to perform as well as the best diode pumped Nd:YAG lasers in terms of threshold power, photon slope efficiency and internal loss. The power slope efficiency is lower due to the lower quantum defect and the nonunity excitation transfer efficiency. The measured threshold power is among the lowest reported for any diode pumped material. The broad bandwidth tolerance for diode pumping is anticipated to reduce the costs of the semiconductor pump, allowing this technology to become more accessible. Moreover, in diode pumping the 1.06 μm transition with visible diodes, this work has demonstrated the extended versatility of diodes which had previously been used to pump only the Cr^{3+} tunable vibronic lasers.

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